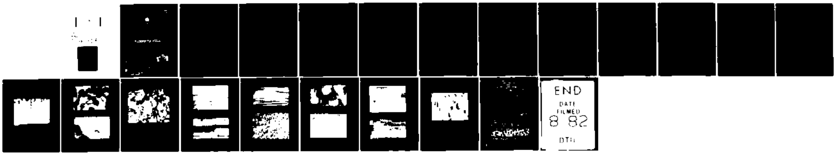
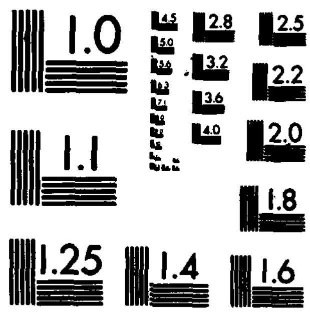
AD-A116 313 ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (ENGLAND) F/G 11/4
SOME FUNDAMENTAL ASPECTS OF COMPOSITES FRACTOGRAPHY.(U)
OCT 81 D PURSLOW
UNCLASSIFIED RAE-TR-81127 DRIC-BR-82874 NL





MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

UDC 661.66-426 : 678.046 : 620.184.6

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 81127

Received for printing 15 October 1981

SOME FUNDAMENTAL ASPECTS OF COMPOSITES FRACTOGRAPHY

by

D. Purslow

(CFRP)

SUMMARY

This Report describes micromechanical research which has been undertaken in order to acquire a detailed understanding of the fracture behaviour of carbon-fibre-reinforced plastics and to establish the expertise necessary to analyse successfully the fracture modes, failure sequence and hence the initial cause of breakdown of aerospace structures made from CFRP. A concise review of some of the more fundamental fractographic aspects of the work is given, from an examination of failure modes in unidirectional CFRP to more general discussion of the fracture of multidirectional material.

This Report is based on an article of the same title published in Composites, 12, No.4, October 1981.

Departmental Reference: Structures BF/B/911

LIST OF CONTENTS

1 INTRODUCTION

Aerospace applications of carbon fibre reinforced plastics (CFRP) are many and diverse. Over more than a decade the use of CFRP has developed from the simple beginnings of control struts and small aerodynamic trimmers to complete carbon fibre wings. Indeed the 'all-composite' aircraft is now a reality. The efficient design of such structures requires a detailed understanding of the fracture behaviour of the material and the modes of failure of the component - knowledge which is also necessary for airworthiness flight clearance and the post-mortem examination of failed components.

A programme of research into the micromechanics of failure has been undertaken in order to provide the basis for such a fractographic understanding and to establish the expertise necessary to analyse successfully the fracture modes, failure sequence and initial cause of CFRP structural breakdown. The detailed results of this research will be published as a series of technical reports. It is timely however that a summary of the work to date should be available and it is the purpose of this Report to provide a résumé of some of the more fundamental fractographic aspects of the work. Axial tension in unidirectional material will be described in some depth to illustrate the degree of understanding of failure processes obtainable by detailed fractographic investigation. Off-axis tension, shear, compression and flexure in unidirectional laminates together with a number of failure modes in multidirectional material will also be considered. Within the scope of this Report, it must be realised that it is impossible to illustrate in detail every aspect which is described.

2 TECHNIQUES

The high strength CFRP laminates used for this investigation were fabricated in an autoclave to a nominal thickness of 2 mm at approximately 65% fibre volume fraction and void content of less than 0.5%. Test coupons in which a known mode of failure could be produced were used to generate fracture surfaces in both unidirectional and multidirectional laminates. All or part of the fracture surface of each coupon was mounted on a specimen stub and provided with a gold conducting surface by evaporation in preparation for examination in a scanning electron microscope.

3 AXIAL TENSION FAILURES IN UNIDIRECTIONAL LAMINATES

The general appearance of these failures depends largely on the strength of the fibre-matrix bond. The comparatively simple, planar fracture surface of strongly bonded laminates becomes increasingly complex and fibrous as the bond strength decreases; at the extremes such fractures are referred to as brittle and non-brittle respectively.

A typical brittle failure is shown in Fig 1 in which the origin O and the radiating lines resulting from axially diverging crack propagation are clearly visible. Such lines will be referred to here as 'radials'. Closer examination of the fracture surface reveals similar patterns on many of the individual fibres, as shown in Fig 2. The failure of fibre B has commenced at B and propagated fan-wise across the fibre resulting in the typical radial markings. Also shown in Fig 2 is a fibre which has failed at a surface fault A. It is important to notice that the origin of failure of fibre B is situated on the same axial plane as that of fibre A and at the point of closest proximity of the two fibres. The failure of fibre B, and likewise that of fibre C, is a direct consequence of the failure of fibre A and such failures will be referred to as 'directly attributable failures' (DAFs). By tracking the paths of DAFs in Fig 2, the fracture of the composite may be accurately charted as it progresses from fibre to fibre. Like time-lapse photography, the fibres can almost be heard breaking one by one. The sequences $A \rightarrow B$ and $A \rightarrow C$ have already been determined and may be continued as follows: $C \rightarrow D$, $D \rightarrow E$, $D \rightarrow F$, $F \rightarrow G$, $F \rightarrow H_1$, $H_1 \rightarrow I$; $J \rightarrow K$, $K \rightarrow L$, $L \rightarrow M$, $L \rightarrow N$, $K \rightarrow H_2$, $H_2 \rightarrow P$, $P \rightarrow Q$. The fracture of fibre H is of particular interest since the failures originating locally at A and J have arrived at the same instant causing the failure of fibre H to propagate simultaneously from $H_1 \rightarrow I$ and $H_2 \rightarrow P$. It may also be noted that the failures of fibres Y and Z, whilst propagating in the common overall direction, are not DAFs - this reflects the preference for the crack to progress from fibre to fibre rather than through the matrix.

Where the propagating crack has to cross a relatively large area of resin (Fig 3), lines in the direction of crack growth are produced in the resin by the crack moving in slightly different planes. Such lines in metals fractography are referred to as 'river' markings; they are not due to a slip-stick mechanism.

The concept of DAFs, the ability to recognise radials on the general fracture surface and on individual fibres and the detection of rivers in the matrix are important features in the understanding of tensile fractures. Returning to a larger area of failure such as that shown in Fig 4, these features may be used to trace the fracture process in detail over most of the area. Having indicated the lines of DAFs, matrix rivers and the position of faulty fibres, several further characteristics become apparent. By following the 'root-system' of sequential failures back towards the origin it becomes evident that a whole group of failures may be traced back to the fracture of one fibre, and in addition that the roots emanating from that fibre do not intertwine with others of different origin. This leads to the notion of fracture 'zones' within which all the fibre breaks originate at a single fracture source. At higher magnification the four very small zones, a, b, c and d are found to be self-contained. Within these zones the fibre failures are on a plane axially separated from the general fracture surface, and the directions of the radials indicate that the failures of the fibres within that zone were not part of the ultimate failure process. Hence it may be deduced that these four zones, and others outside the area considered, broke independently before ultimate failure, the forces associated with their fracture being insufficient to precipitate ultimate failure at the overall stress to which the composite was at the time subjected. These comments also apply to individual fibres (such as S, Fig 4) which may fail at a fault. The fibres indicated on Fig 4 to have failed at a fault are only those which are readily recognisable; there are many more which remain undetected. Isolated fractures in a different axial plane to the local failure are referred to as fibre 'pull-out' and are one of the main features of non-brittle failures. The fracture surface along the axis of pulled-out fibres is normally due to shear and will be dealt with under that topic. Many of the zones originate at a fibre fault and frequently it is found that the initiation of a zone at a fibre fault is associated with an axial change in the fracture plane. It is this characteristic which gives rise to the majority of the hill-and-valley radials evident on the overall fracture surface as in Fig 1. Another feature, evident from Fig 3, is the ability of the propagating crack to cross relatively large areas of resin and precipitate directly attributable fibre failure on the other side. It has not been possible to account for this using static stress concentration factor considerations and, in view of the viscoelastic nature of the matrix, this leads to the concept of a dynamic stress concentration factor. The current work has provided some evidence for the reality of such a concept, but details are outside the scope of this Report.

It is now possible, from the information on Fig 4, to describe the likely sequence of events leading to ultimate failure. Zones a, b, c, d and many of the individual faulty fibres failed prematurely. Ultimate failure originated at e followed by the sequence $f \rightarrow g \rightarrow h \rightarrow j \rightarrow k \rightarrow m \rightarrow n \rightarrow p \rightarrow q \rightarrow r$. Although many fibres do fracture before total failure of the composite, it is evident from these considerations that final failure is not a mere linking-up of pre-existing failures - in fact such premature failures can be seen to have little effect generally on the final tensile fracture process.

The comments so far have been concerned mainly with brittle failures. Similar examination of non-brittle fractures shows that identical processes are in operation at failure, the differences being the effects of the reduced strength of the fibre-matrix bond on the relative importance of the various processes. The amount of fibre pull-out is greater, there are fewer DAFs and more, but less well-defined, zones. There is also increased likelihood of more than one independent failure origin - a kind of 'maxi-zone' notion. It is not surprising therefore that the precise location of fracture origin is more difficult to determine.

One last point may be made regarding tensile fracture. The strength of the matrix and of the fibre-matrix bond is affected by exposure to moisture and the only effective quantifiable fractographic method of relating the degree of moisture uptake to the failure process is the change in amount of fibre pull-out. It might be expected that the presence of moisture would weaken the fibre-matrix bond and hence increase the amount of pull-out. By measuring the length distribution of fibre pull-out the current work has in fact shown that for a single-phase matrix the amount of pull-out decreased with increase in exposure, whilst that of a two-phase plasticised resin matrix increased with increase in exposure. However, with both resins the shear and flexural strengths decreased with increase in exposure.

4 OFF-AXIS TENSION FAILURES IN UNIDIRECTIONAL LAMINATES

A series of coupons was tested such that the angle between the fibre axis and loading axis was 90°, 45°, 30°, 20°, 15°, 10° and 7°. Fig 5 shows a typical 90° (transverse tension) fracture surface where failure has originated at an inclusion A. Radials, consisting of fibre ends, are generated as the crack propagates on slightly different planes breaking the fibres individually or in small groups in flexure or tension as the crack progresses. Since the failure is largely in the matrix and at the fibre-matrix interface it is not surprising that closer inspection reveals many matrix rivers in the same direction as the radials. It is important to note that, at all angles from 45° to 7°

inclusive, *all* the coupon failures were initiated by a transverse tensile fracture originating at one edge with radials running well into the failure surface. Apart from the 7° coupons, the remainder of the failure surface then changed at some stage to a shear fracture (see shear section). The 7° specimens subsequently failed in an axial tension mode, any shear fracture being post-failure damage. It must be noted therefore that, despite the existence of shear fractures on the failure surfaces of off-axis coupons, this test is not suitable for the determination of in-plane shear strengths, particularly since at no angle did the sustained shear stress attain as much as 75% of the known shear strength of the material.

5 SHEAR FAILURES IN UNIDIRECTIONAL LAMINATES

Shear cracks rarely, if ever, propagate by extension of a single crack, as has been shown to be the usual case in tension, and in fact shear failures are most likely to originate as tensile fractures of the matrix. In order to justify this surprising statement, consider for a moment a two-dimensional model of a pair of parallel, infinitely stiff fibres joined by a thin layer of resin. Application of a relative axial movement between adjacent ends of the fibres must result in an identical relative movement in the fibres at their other ends. In other words, apart from a small area at each end, the shear strain in the matrix is constant along the length of the fibres. The high axial modulus of carbon fibres compared to that of the resin matrix means that this hypothetical situation is often approached in practice as will be seen later. A typical shear fracture containing a broken fibre A, is shown in Fig 6. The compression fracture of this fibre indicates that the mating failure surface moved in the direction of the arrow. Similarly, a fibre tensile failure in this position would occur if the relative movements were reversed. The surface of a typical shear fracture is a mixture of such fibre failures, interface failures evident either as a fibre surface or a fibre imprint in the matrix, and failure of the matrix itself. The variation in topography within one coupon fracture surface is such that no reliable quantitative assessment of either the fibre-matrix bond strength or moisture degradation is possible from a shear failure. Since the shear strength of CFRP is largely determined by the strength of the matrix and of the fibre-matrix bond, it is prudent to investigate the fracture of the resin itself. From Fig 6 the resin fracture surface can be seen to consist almost entirely of rows of 'cusps', as at B. The formation of a cusp commences as a tensile failure perpendicular to the tensile component of the resolved applied shear stress, as shown at A in Fig 7. Shear failure does not propagate by simple extension of such a crack, because of the high fibre stiffness relative to the matrix as explained at the outset of this section. A line of these tensile failures develops and with increasing shear strain the number of these fractures and their individual length increases. As the individual cracks extend away from the shear plane, they bend over to become the characteristic 'S' form (Fig 7). Failure occurs along the line of cracks when these tensile fractures finally and simultaneously coalesce. The cusps thus formed are absolutely characteristic and wherever they occur are indicative of failure due to applied shear stress. Even where there is a high shear stress gradient (as in the out-of-plane distortion due to impact, described later), the shear cracks originate in the same way, albeit over a very limited area.

Two further points may be noted also. Firstly, in the case of shear, defects such as voids and inclusions do not act as failure origins but simply weaken a given plane and therefore enhance the likelihood of ultimate fracture occurring through that plane. Secondly, where, in a tensile failure, individual fibres or blocks of fibres pull-out of the fracture surface, they do so by shear along the fibre axis and thus matrix features on pulled-out fibres may be generally explained by the shear processes outlined in this section.

6 AXIAL COMPRESSION FAILURES IN UNIDIRECTIONAL LAMINATES

Fractographic analysis of compression failures is complicated by several problems, not least of which is the frequent obliteration of the initiating fracture by post-failure damage due to relative movement of the fractured surfaces in contact. In addition, compression cracks cannot propagate over large areas, as in the simple tensile crack opening process, because of the significant bearing loads sustainable between the fractured surfaces. Furthermore, fracture initiation may occur by one of a number of modes. Even with carefully designed test coupons, failures often occur by overall (macro) buckling of the specimen in a combined flexural-compressive failure. Maximum compressive strength is achieved when failure occurs by shear of the fibres, but in many cases the relatively low matrix modulus and weak fibre-matrix bond result in premature failure by micro-buckling. Thus it should be noted here that a reduction in the fibre-matrix bond strength, which produces tougher and often stronger composites in tension, may reduce the ultimate compressive strength.

A typical compressive fracture is shown in Fig 8 where the whole failure surface is at an angle to the loading axis. The area at A illustrates the rows of fibres which, like fainting soldiers on parade, have buckled along axes parallel to the line a-a . Lines such as a-a normally lie perpendicular to the fibre axes, but not necessarily parallel to the plane of the laminae. In fact, by considering the orientation of such buckling lines, which tend to lie perpendicular to the direction of crack propagation, the area of failure origin frequently may be determined. Fig 9 shows such fibre failures in detail. The buckle axes, such as a-a , separate compressive failures C from tensile failures T on the individual fibres. This micro-buckling may occur on several planes and indeed the overall fracture surfaces sometimes consists entirely of a series of steps, the height of each step being a multiple of half the buckling wavelength. Thus, the relative positions of the compressive/tensile facets of the individual fibres are unlikely to be informative since they will reverse at each step. During the progression of micro-buckling failure, the relative movements of areas of already broken fibres which are in contact may be broken further in shear by abrasion, as at B (Fig 8). Since, conversely, compressive failures which originate as fibre shear fractures may, during propagation, initiate areas of micro-buckling, it is evident that frequently the true nature of the compressive fracture is difficult to determine. Further fractographic analysis may elucidate features which occur uniquely in failures originating as either shear or micro-buckling.

7 FLEXURAL FAILURES IN UNIDIRECTIONAL LAMINATES

Consider failures generated by the three-point bend method where failure occurs at the central roller. As in the case of individual fibres under compression in the previous section, the surface of such a flexural failure normally consists of areas of tensile fracture and compressive fracture, the boundary between them being parallel and often close to the neutral axis of the laminate. Usually, flexural failure originates on the compression surface, due to the lower strength of CFRP in compression relative to tension and the stress concentration generated by the central roller. The crack then moves towards the neutral axis, but since, as in the case of applied compression, the fractured surfaces are capable of sustaining substantial loads (stabilised laterally by the roller) the position of the neutral axis may not move significantly. As the crack approaches the neutral axis it moves into a field of decreasing compressive stress and increasing interlaminar shear stress, the compressive fracture frequently stopping at a shear crack. Increased tensile strain in the opposite face initiates a rapid failure towards the neutral axis. Such a fracture is shown in Fig 10. When the initial failure is on the tensile face, the neutral axis will rapidly move away from the surface as the crack propagates, resulting in most, if not all, of the fracture being of a tensile nature. In more general cases of flexure, the position of the boundary between compressive and tensile fracture will give some indication of the conditions of flexure which existed.

It was mentioned when considering transverse tensile failures, that some fibres are broken in flexure. This occurs when individual or small groups of fibres become debonded at different positions from both fracture surfaces (*ie* they are 'tied' to both surfaces). At ultimate failure such fibres are bent into an 'S' shape and fracture occurs at one of the two points of maximum flexure, the position of the compressive/tensile facets of the individual flexural failures depending at which of the maxima the break took place. Hence frequently it arises that these flexural fractures appear to indicate that they have been bent into, rather than away from, the overall transverse tensile fracture surface.

8 TENSION FAILURES IN CROSS-PLY LAMINATES

The CFRP here referred to as cross-ply consist of balanced laminates with fibres in the direction of the loading axis (0°, axial) and perpendicular to the loading axis (90°, transverse) with equal proportions but no given stacking sequence. The ultimate strength of such a material is dependent almost entirely on the strength of the axial plies and in the ensuing discussion the tensile stress referred to will be that in the axial plies. Application of increasing axial tensile stress will cause cracking in the transverse plies well before ultimate failure - the thicker each group of transverse plies the earlier cracking commences. The cracks in the transverse laminae initiate at the mid-thickness and spread through the thickness to (but do not penetrate) the axial plies. In transverse plies containing say two layers, the spread of the cracks along the fibres will cause the crack to bifurcate due to slight differences in the fibre orientation of the two layers. The crack spacing is regular and a function of the applied tensile stress; as the stress is increased the crack spacing decreases. Whilst for most stacking sequences the existence of transverse cracks premature to failure has no significant influence on the attainable tensile strength, their presence has two important fractographic consequences.

Firstly, it has been noted that for a given laminate the transverse crack spacing is related to the applied axial stress. Thus, where for some reason delamination occurs before ultimate failure, post-failure analysis of the crack spacing in the transverse plies at the delamination will give a good indication of the stress at which delamination occurred. Such a feature is illustrated in Fig 11 where at A the crack spacing is that occurring at ultimate failure, whereas at B delamination occurred at about 60% ultimate. Area B is at the edge of a hole and premature delamination relieved the stress concentration due to the hole, allowing the composite to sustain a higher stress than its undelaminated counterpart!

The second fractographic aspect of transverse cracking occurs at ultimate failure. Whilst the pre-existence of transverse cracks has little effect on the failing stress of the laminate, it has a significant effect on the manner in which the crack propagates at ultimate failure, which in turn reveals an important fractographic characteristic. Using the techniques described earlier for axial and transverse tension, it is possible to trace the failure sequence in a cross-ply fracture such as that illustrated in Fig 12. Failure originated in the axial plies at A and spread as indicated by the arrows. The significant point to notice is that, apart from the initial failure zone at A, all the axial ply failures are in the same axial plane as the adjacent, pre-existing transverse fractures (*eg* BC, DEF, GHJ). Indeed, once the initial failure has occurred at some stress concentration such as at A, not necessarily associated with the transverse failures, and a certain limited number of fibres have failed (*ie* sufficient energy released or crack velocity attained?), the further propagation of the crack is 'focussed' by the transverse cracks. The exact mechanism is not fully understood, but detailed fractographic examination leaves no doubt that the positions of the fractures in the axial plies are dictated by pre-existing transverse cracks. Frequently, failure in one set of axial plies will be initiated by cracks in both the adjacent transverse plies. A diagnostic feature of such dual origins is the failure of one set of plies at two different levels corresponding to the levels of the transverse cracks (see, for example, C/D and F/G in Fig 12). Since the general movement of the progressing fracture is away from A, hill-and-valley radials (as in axial tension) develop at an angle to the plane of the laminae and meet from either side some distance into the axial plies. This leads to the repetitive occurrence of 'chevron' markings in the axial plies which act as arrow-heads pointing in the direction of crack propagation. Similar radials and rivers occur in the transverse failures, but pointing in the reverse direction. These features are not only characteristic of simple cases of cross-ply tension. For example, $\pm 45^{\circ}$ webs subjected to shear stress frequently fail due to the tensile component, particularly where cut-outs occur, the chevrons produced acting as finger-prints in detecting the direction of crack propagation.

9 FAILURE MODES IN MULTIDIRECTIONAL LAMINATES

One of the most common lay-ups is the $0^o \pm 45^o$ balanced laminate containing 50% 0^o plies dispersed through the composite (*eg* 0 + -00 - +0). Consider first the in-plane failure modes associated with such a laminate. The 0^o fibres are normally designed to carry the primary tensile (or compressive) loads and the ultimate strength of the laminate is largely determined by these fibres. However, as in the cross-ply case, transverse cracking in one or both of the off-axis directions occurs well before failure. In a brittle laminate, ultimate failure in the 0^o plies unassociated with the off-axis cracks may well propagate directly into the off-axis plies causing tensile fractures along their axes. In many cases, particularly where the propagating fracture meets an existing off-axis crack, delaminations between the 0^o and 45^o plies will also occur. In this case the pre-existing crack in, say, the $+45^o$ ply will cause a brittle tensile failure in the -45^o along the $+45^o$ line with chevron markings as in the cross-ply laminates.

In non-brittle composites the off-axis cracks usually precipitate considerable delamination before failure and the fracture of each ply may be considered as a separate tensile failure. In fact, in both brittle and non-brittle laminates, whatever the direction of primary tensile load, each orientation of plies may be analysed as for the unidirectional and cross-ply cases, resolution of the failure axes indicating the previously unknown orientation of loading. For example, if all the $+45^o$ plies fail in axial tension, with transverse tensile failures in adjacent -45^o plies (as in the cross-ply case), and delamination occurs at most of the 0^o boundaries, then the primary applied load was likely to have been tension at about $+45^o$. The situation with compression is similar, except that premature delamination is more frequent and subsequent overall buckling often prevents true compressive fracture.

In the case of shear, the initial failures are almost invariably of the 'cross-ply tension' type in the direction of the maximum resolved tensile stress, the resulting chevrons in the '0/90' plies again being indicative of the direction of tensile (not shear) crack propagation.

One out-of-plane case will be considered here which indicates the sort of fractographic information available from examination of other similar cases. Minor impact damage, such as that caused by dropping a tool onto a uniformly supported multidirectional laminate, will cause delamination and cracking to occur over an area about 10 mm in radius, as detected by ultrasonic inspection. The impact produces sharp out-of-plane bending, the laminae remaining stationary relative to one another along the line of impact. Increasing inter-laminar shear strain occurs over a short distance from the impact, which then decreases to zero again where the laminate is undeformed, the area of delamination being determined by the extent of the shear strain. Not surprisingly, the area, in the line of impact shows compressive damage and debris at the delamination; on the opposite face to the impact some transverse tensile cracking parallel to the fibres occurs. Delamination normally takes place at the boundary between plies of different orientation and in this plane of delamination the shear deformation occurs radially, centred on the compressive area. The interesting feature is that small changes take place in the position of the plane of delamination, even to the extent of it moving to an adjacent ply of different fibre orientation. These changes in the plane of delamination are such that the direction of shear strain tends to be aligned with the fibre direction. Thus shear failure occurs preferentially along the axis of the fibres rather than across them since it is the line of least resistance. Where shear failure does occur at an angle to both adjacent plies (Fig 13), it takes place at the interlaminar boundary, the cusps occurring at an angle to the fibre directions (a-a, b-b) but perpendicular to the direction of shear.

As described in the paragraph on shear, the resin cusps will indicate the relative movement of the delaminated surfaces, thus indirectly diagnosing the side from which the impact occurred. The resin cusps will not indicate the direction of crack propagation, although such a sharp out-of-plane excursion is one of the few occasions where a shear crack can be clearly seen to 'start' and 'stop'.

10 CONCLUSION

In this outline of the fractography of CFRP it has not been possible to give more than a glimpse of the fundamental aspects which have been revealed. Neither has it been within the scope of this Report to describe the many cases where application of these techniques to failed structures has led to a knowledge of the nature and origin of fracture. What has been imparted, it is hoped, is an understanding of how fracture actually occurs, an insight into some of the various characteristic features, the effects of such parameters as fibre-matrix bond strength on the failure modes and hence an indication of the power of fractography in the analysis of the failure processes in CFRP.

The work to date has also greatly assisted in both the assessment of the significance of micro-defects (*eg* voids, fibre faults etc) on the behaviour of CFRP and in the understanding of notch sensitivity. Much remains to be accomplished including further work on some of the topics discussed above, in areas such as fatigue and environmental effects, and on other fibre composites such as glass, Kevlar and boron.

Acknowledgments

Many thanks are due to the numerous colleagues who supplied coupon fractures for examination.

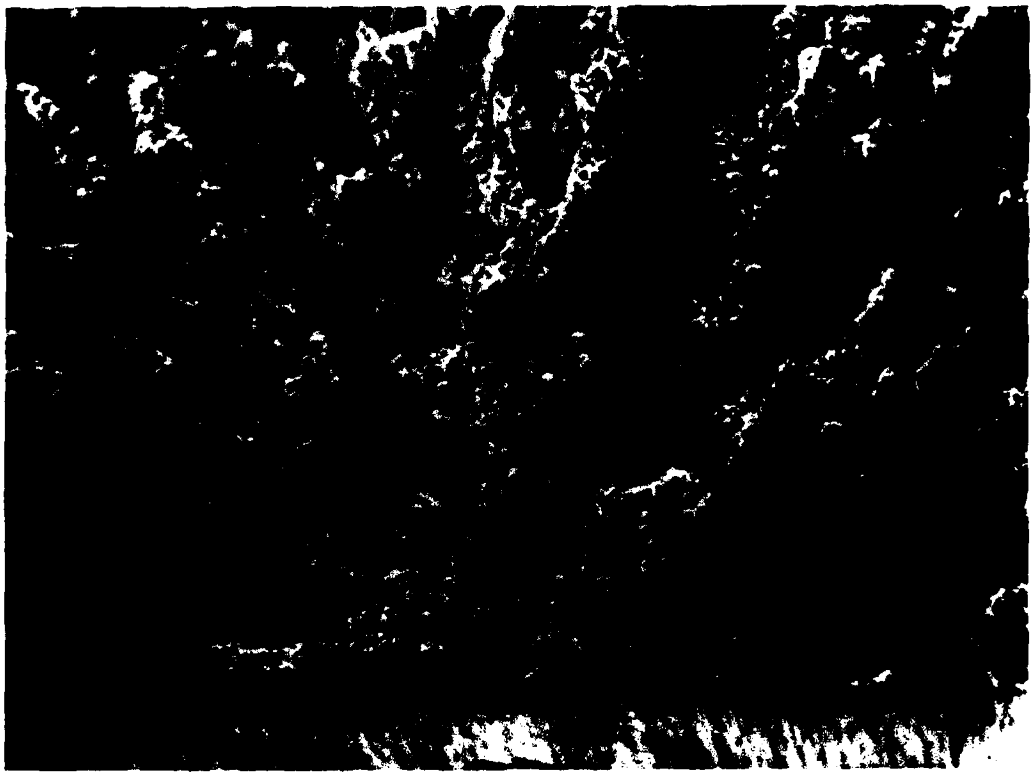
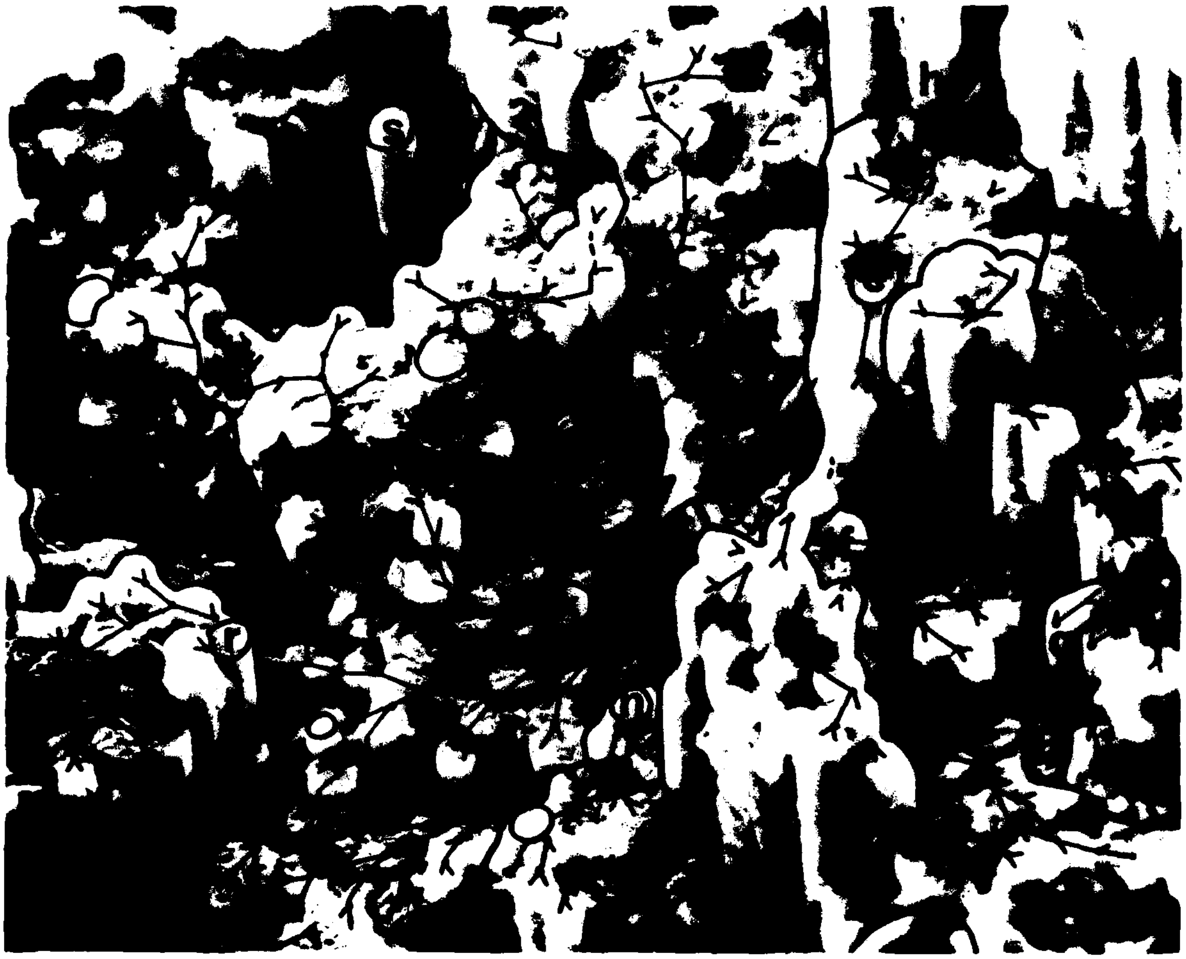


Fig 1 Brittle tension failure (x50)

Fig 2 Directly attributable fibre failures (x3000)

Fig 3 Resin matrix fracture (x7000)

TR 81127 C17273



< Fibre radials — Rivers

DAF — Dual fracture

Faulty fibre — Zones

TR 81127 C17274

Fig 4 Origin of tensile failure (x1000)

Fig 5 Transverse tensile failure (x50)

Fig 6 Shear failure (x2500)

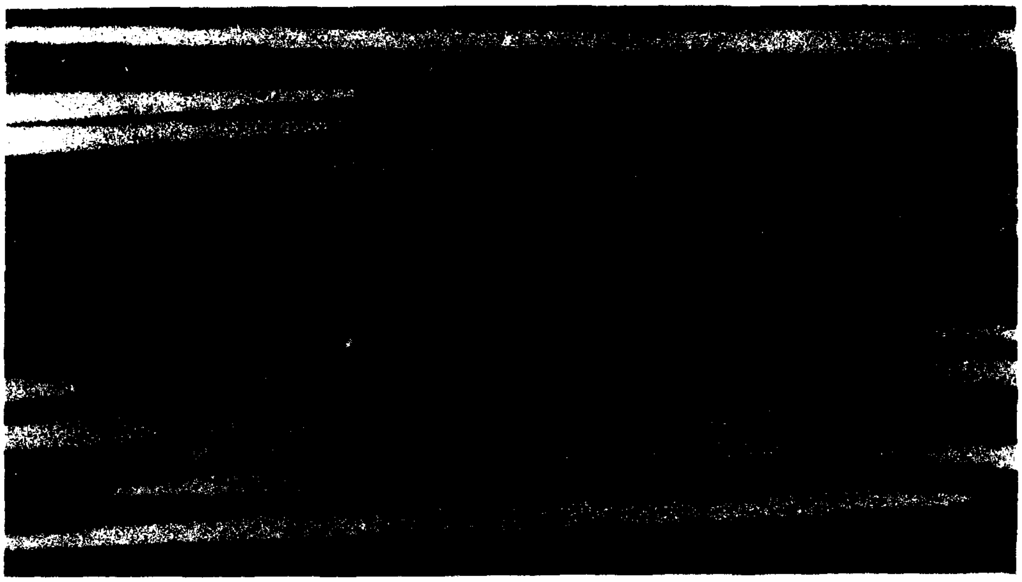


Fig 7 Initiation of shear failure (x600)

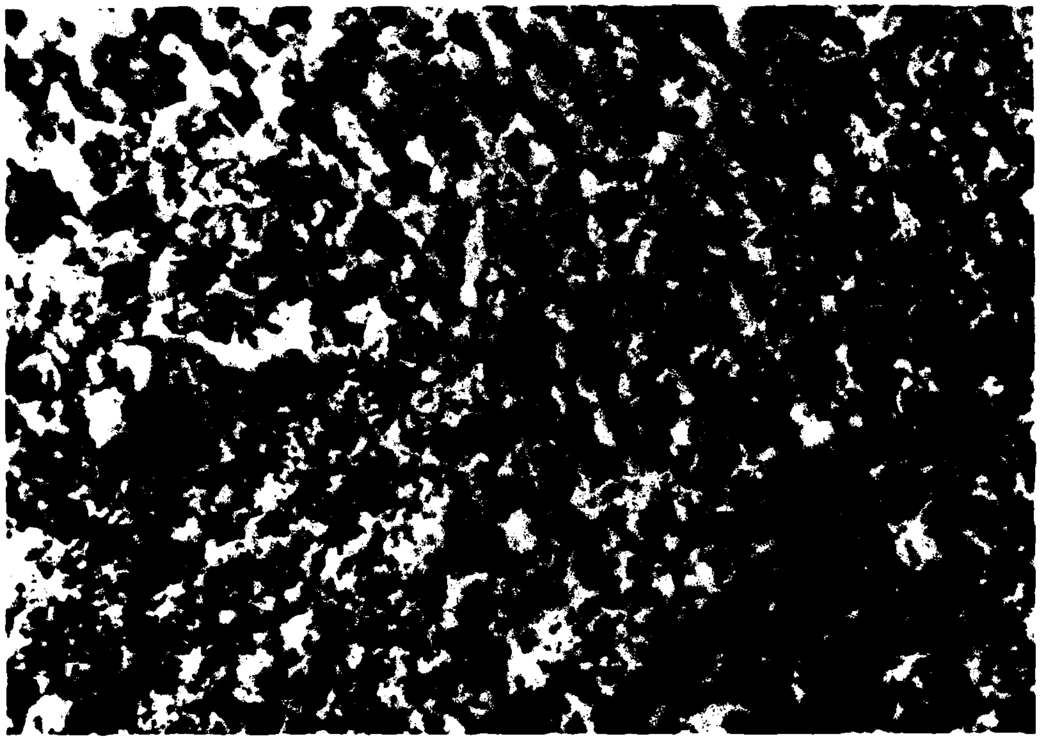


Fig 8 Compression failure (x700)

TR 81127 C17276

Fig 9 Compression micro-buckling (x4000)

Fig 10 Flexural failure (x80)

Fig 11 Transverse cracking in cross-ply laminates (x10)

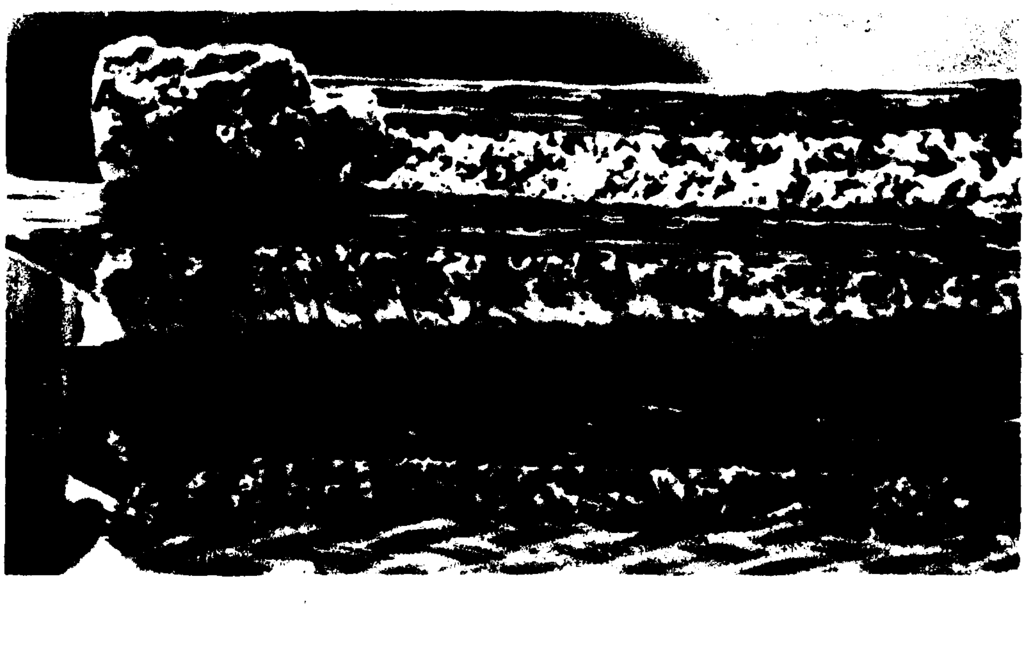


Fig 12 Tension failure in cross-ply laminates (x30)

Fig 13

Fig 13 Interlaminar shear failure due to out-of-plane impact (x1500)

ATE
LME
-8